ADVANCED FIBER BRAGG GRATINGS FOR MICROWAVE PHOTONICS APPLICATIONS

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ABSTRACT

Owing to the unique features of flexible spectral characteristics, low loss, light weight, compact footprint, and compatibility with other fiber-optic elements, fiber Bragg gratings (FBGs) have been extensively used in various microwave photonics systems. In this work, the recent development in employing advanced FBGs for various microwave photonics applications are reviewed, with emphasis on microwave arbitrary waveform generation and photonic microwave filtering. An innovative FBG sensor interrogation scheme using microwave photonics techniques is also presented.

Keywords: Arbitrary waveform generation, dispersive Fourier transform, *fiber Bragg grating, microwave photonics*

1. INTRODUCTION

Over the past few decades, extensive efforts have been devoted in the emerging interdisciplinary field of microwave photonics from both academic and industry sectors, making it an attractive solution in widespread applications such as broadband wireless communications, radar, sensor networks, medical imaging, instrumentation and electronic warfare systems [1,2].

A fiber Bragg grating (FBG) is a unique in-fiber device where the refractive index of the fiber core is modulated periodically via UV illumination [3]. Owing to their inherent compatibility to other fiber-optic components and flexible spectral characteristics [4], FBGs have been widely used in widespread microwave photonics systems [5]. In general, an FBG can serve as a dispersion delay-line element, a narrowband optical band-pass/band-stop filter, or a broadband optical spectral shaper with arbitrary spectral response. In this paper, our recent work on applying advanced FBGs in various microwave photonic applications, such as microwave arbitrary waveform generation, photonic microwave signal processing and ultrafast FBG sensor interrogation, are reviewed.

2. FBGS FOR MICROWAVE ARBITRARY WAVEFORM GENERATION

Photonic generation of high-frequency and large-bandwidth microwave arbitrary waveforms has been of great research interest due to the advantages such as high speed and broad bandwidth provided by optics [6]. Various techniques have been demonstrated for microwave arbitrary waveform generation, such as direct space-to-time pulse shaping [7] and temporal pulse shaping (TPS) [8].

Another widely used photonic microwave arbitrary waveform generation technique is based on spectral shaping and wavelength-to-time mapping (SS-WTM) in a dispersive element [9]. By properly designing the response of an optical spectral filter, a temporal pulse with the shape identical to the shaped-spectrum is obtained after the mapping process. The physics is also known as dispersive Fourier transform [10], as the intensity profile of the dispersed waveform is the Fourier transform of the original input optical pulse.

Thanks to its flexible spectral response, an FBG can be used in a microwave arbitrary waveform generator to achieve spectral shaping. Various FBG-based optical spectral filters have been proposed and demonstrated based on this concept. For example, to generate highly chirped microwave and millimeter-wave (mm-wave) pulses, which have been widely used in modern radar systems to improve range resolution, an optical spectral shaper with chirped spectral response is required. This can be achieved using superimposed chirped FBGs [11] or a fiber Sagnac loop mirror incorporating a chirped FBG [12]. In addition, if a uniform comb filter is used as the spectral filter, chirped microwave waveforms can be generated based on nonlinear frequency-to-time mapping using a dispersive element with higher-order dispersions, for example, a nonlinear chirped FBG [13].

To further simplify the system structure, a single linearly chirped FBG, which integrates both functionalities of spectral shaping and wavelength-to-time mapping, has been demonstrated to generate arbitrary-waveform microwave pulses [14]. Figure 1 shows the system diagram. The chirped FBG is properly designed to have a particular spectral response according to the desired waveform. The inherent linear group delay response guarantees the perfect wavelength-to-time mapping. Most recently, a new approach using a spatially-discrete chirped FBG to generate large time-bandwidth product (TBWP) microwave waveforms has been demonstrated [15]. Compared to the system in [14], the spatially-discrete FBG provides one extra feature: the mapped temporal waveform can be further time shifted by the same FBG. Linearly chirped, frequency hopped and phase coded microwave waveforms have been generated by properly controlling the temporal shifts.

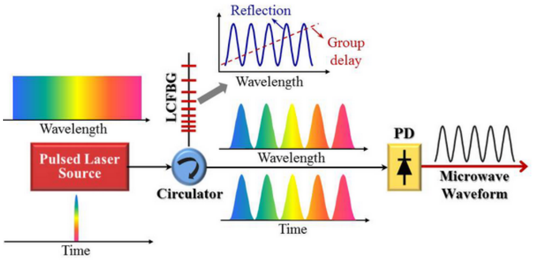

Fig. 1. Microwave arbitrary waveform generation based on simultaneous spectral shaping and wavelength-to-time mapping in a single linearly chirped FBG.

3. FBGS FOR MICROWAVE PHOTONIC SIGNAL PROCESSING

As discussed in Section 2, microwave photonics provides a promising solution for generating microwave waveforms with high frequency and large bandwidth. On the other hand, processing of such microwave signals becomes a challenge for conventional electronic solutions. It is therefore desirable that the generated high frequency microwave waveforms can be processed in the optical domain as well. Microwave photonic signal processing can overcome the inherent bottlenecks caused by limited analogue bandwidth of conventional electrical circuits and limited sampling speeds in digital signal processors [16]. Particularly, the superior and unique spectral properties of FBGs can be applied to develop novel photonic signal processing units featuring not only high time-bandwidth product capabilities for processing high-speed signals but also highly adaptive and reconfigurable operation.

A photonic microwave filter is usually used to process microwave signals and waveforms in the optical domain. A finite impulse response (FIR) photonic microwave filter can usually be implemented in a weighted multi-tap delay-line structure. An array of uniform FBGs have been used to provide such a delay-line structure [17]. The time delay difference is determined by the physical separation of adjacent FBGs, and the tap coefficients are dependent on the reflectivities of the uniform FBGs. In our recent design, a single spatially-discrete chirped FBG substituted the uniform FBG array as the delay-line unit [18]. Here the spatially-discrete chirped FBG performs simultaneously three functions: to slice the spectrum of a broadband optical source for generating filter taps, to provide time delays for different taps, and to tailor the weights of the filter taps, as shown in Fig. 2(a). As the time delay between taps can be customized, a nonuniformly spaced FIR microwave photonic filter can be implemented. One unique feature of such a filter is that equivalent negative and complex filter coefficients can be achieved using all-positive filter taps.

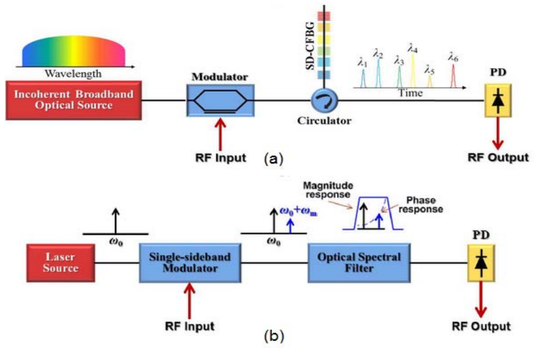

Fig. 2. FBG-based microwave photonic filters. (a) A nonuniformly spaced microwave photonic delay-line filter using a spatially discrete chirped FBG. (b) A microwave photonic filter based on optical filter response to microwave filter response conversion.

An alternative approach for building microwave photonic filters is based on optical filter response to microwave filter response conversion. The key advantage of this method is that only one optical wavelength is required, while delay-line FIR filters usually need multiple optical wavelengths. As shown in Fig. 2(b), the optical carrier is modulated by the microwave signal to be processed in a single-sideband modulator. An optical spectral filter changes the amplitude and/or phase of the single modulation sideband. The microwave signal is recovered by beating the unchanged optical carrier and the modified sideband at a photodetector. In this way, the optical filter response can be transferred to the microwave filter response. A uniform FBG has been used as an optical spectral filter [19]. Its sharp linear group delay response has been transferred to a microwave photonic filter with a strong quadratic phase response (linear group delay response). Such a microwave photonic filter is highly attractive in chirped microwave pulse compression.

4. REAL-TIME FBG SENSOR INTERROGATION

Microwave photonics does not only use FBGs to achieve various functions, it also creates new techniques to decode FBG sensors. One example is ultrafast real-time FBG sensor interrogation based on temporal spectroscopy.

Real-time diagnostics of fast-vibrating objects, such as a running aircraft engine, relies on high-speed sensor interrogation systems. Most of the fiber grating sensors are functioning based on wavelength modulation, in which the sensed information is directly encoded as the grating wavelength change. To monitor the wavelength shift of an FBG, various FBG sensor interrogation techniques have been developed, with the maximum interrogation speed of only tens of kHz. Temporal-spectroscopy technique, which uses a chirped optical pulse to map the optical spectrum to a temporal waveform as shown in Fig. 3, has been a promising technique for real-time FBG sensor interrogation in the megahertz regime [20].

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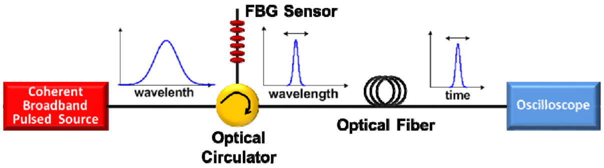

Fig. 3. Real-time FBG sensor interrogation system based on temporal spectroscopy.

In addition, by applying chirped pulse compression technique in the temporal-spectroscopy-based FBG sensor interrogation system, both spectral resolution and signal-to-noise ratio can be improved [21]. Recently, to overcome the fundamental tradeoff between the interrogation speed and resolution in a temporal-spectroscopy-based FBG sensor interrogation system, a novel technique to achieve ultrafast and ultrahigh-resolution interrogation of FBG sensors based on interferometric temporal spectroscopy has been proposed and experimentally demonstrated [22]. Direct measurement of absolute optical wavelength shift has been converted to the measurement of a microwave beating frequency. The latter has much higher measurement resolution due to the fact that an interferometer has an inherently high sensitivity and equivalent resolution of an electrical spectrum analyzer is higher than that of an optical spectrum analyzer.

7. CONSLUSION

In summary, due to the unique filtering properties and versatility as an in-fiber element, FBGs have become a promising solution in a variety of microwave photonics applications. This paper reviews some FBG-based microwave photonic systems, with advantages of small size, low loss, low cost, good stability, and high compatibility with other well-developed fiber-optic devices.

6. ACKNOWLEDGEMENT

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